PRESSURE SENSITIVE SURFACES

Cross-Reference to Related Application

This is a Continuation of Application No. 10/184,080, filed on 28 June 2002 and entitled PRESSURE SENSITIVE SURFACES.

Technical Field

[0001] This invention relates to pressure-sensitive devices. More particularly, the invention concerns structures for accurately localizing point sources of pressure and methods for determining the location and force of a point pressure source on a pressure-sensing surface. The invention may be applied to provide interfaces to electronic devices.

Background

[0002] It is known to make pressure-sensitive surfaces by instrumenting a mat or other structure which includes a surface region with an array of pressure sensing elements. For example, an array of pressure sensors of the type described in PCT publication No. WO 99/04234 (Reimer, et al.), can be used to detect the location and pressure applied by several simultaneous points of contact.

[0003] The surface may be covered with a membrane as described, for example, in WO 00/73982 (Inkster). Such membranes can cause problems, however. A membrane can distribute pressure so that touching at one location causes signals from the pressure sensors in a surrounding area. The prior pressure-sensitive surfaces described above provide no way to isolate the response of a set of pressure sensors from neighboring ones.

[0004] In conventional pressure-sensitive structures which include a membrane overlying an array of pressure sensors, the membrane distributes pressure imposed by an indentor radially outwardly from the indentor in a generally uniform manner. The inventors have determined that by selecting the properties of a membrane, it is possible to control how force from an indentor will be distributed over pressure sensors in a pressure-sensitive structure. This can be very beneficial in some applications.

Summary of the Invention

[0005] In general, the invention relates to position sensing surfaces wherein individual sensing elements located on a substrate measure pressure at specific locations. In many cases it is desirable to know the location of the applied pressure, which may not be directly over one of the sensing elements. In such applications, a membrane positioned adjacent the substrate can distribute the pressure over several nearby pressure sensing elements, which enables one to compute the pressure at any point by interpolating between sensors. This also provides a means to reduce the total number of sensing elements for a resulting reduction in costs and complexity.

[0006] The sensitivity of the device may be improved by the use of protrusions on the membrane, each of which is located so as to contact an individual sensing element. As can be imagined, when a membrane is constructed in this manner, any force applied to the membrane is transferred to the individual sensing elements by the protrusions. Since

the total contact area of the protrusions is small, the bearing pressure is concentrated at those protrusions.

[0007] If an “indentor” is used to apply a force to the surface, the location of the indentor may be estimated by means of a centre-of-mass algorithm or other similar mathematical computation. The invention provides to an improved method to accurately compute the indentor location.

[0008] The invention further relates to a position sensor comprising a substrate covered by a membrane. The substrate comprises an array of pressure detecting means. The pressure detecting means may comprise any of a number of systems, including force sensitive resistors, piezo-electric crystals, strain gauge-based sensors, and optical pressure sensors of the type described in WO 99/04234, among others. The type of pressure detecting means may be varied without departing from the invention. One aspect of the invention relates to the use of physical features in the membrane (such as holes or recesses) to tailor the distribution of pressure. Another aspect of this invention relates to position sensors having irregular distributions of pressure sensing elements. Another aspect of this invention provides a way to accurately compute the location of an "indentor" which is applying pressure.

[0009] In one aspect, the invention comprises a position sensor, comprising a substrate covered by a membrane. The substrate includes an array of individual pressure-detecting elements. The membrane has a

non-uniform structure and comprises means for isolating areas of depression of the membrane caused by local application of pressure wherein depression of a first of said areas causes substantially no depression of a second, adjacent area.

[0010] The means for isolating the membrane areas may comprise a slot between the first and second areas. Alternatively, the isolating means may comprise an area in which the membrane is fixed to the substrate. The membrane may be fixed to the substrate in a trough, or depressed portion between the areas. The portions of the membrane adjacent to the trough are not fixedly engaged to the substrate.

[0011] In one embodiment, the membrane comprises at least one depressed region for contacting the substrate. The membrane is separated from the substrate other than at the location at the at least one depressed region.

[0012] The isolated membrane areas have various shapes and may be arranged in regular or irregular arrays. The areas may be one or more of a rectangular, triangular, truncated triangular or irregular-shaped.

[0013] In another aspect, the membrane is partly separated from the substrate, being supported on the substrate by one or more regions of the membrane which contact the substrate. Pressure applied to the membrane is thus transmitted to the substrate solely or substantially at the contact regions.

[0014] In another aspect, the invention comprises a pressure sensing surface comprising a substrate having an array of pressure sensing means and signal processing means to receive pressure information from said sensing means. The signal processor means is programmed to calculate the location and magnitude of force applied to the membrane according to a formulae described herein, in which the sensor is assumed to be generally planar with x, y coordinates describing its surface.

[0015] This specification includes directional references such as "up" and "down" for convenience and ease of understanding. It will be understood that the sensors described herein may be placed in any orientation. The directional references herein are not intended to be limit the invention.

<u>Brief Description of Drawings</u>

[0016] In drawings which illustrate non-limiting embodiments of the invention:

Figure 1 is a sectional profile view of a membrane system according to one embodiment of the invention;

Figure 2 is a plan view of a membrane system according to another embodiment of the invention;

Figure 3 is a plan view of a membrane system according to a further embodiment of the invention;

Figure 4 is a sectional profile view through the membrane system of Figure 3;

Figure 5 is a plan view of a membrane system according to another embodiment of the invention;

Figure 6 is a sectional view along the line A-A in Figure 5; and,

Figure 7 is a sectional view of a membrane system according to a still further embodiment of the invention.

Description

[0017] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0018] A first aspect of the invention relates to constructions for pressure-sensitive devices. Anything which applies a downward force on the surface of such a device is referred to herein as an "indentor". In most applications it is of interest to be able to determine the location and magnitude of force applied to a pressure-sensitive device by one or more indentors.

[0019] Figure 1 shows a membrane system **10** according to a first embodiment of the invention. Membrane system **10** comprises a substrate

12, an overlying flexible membrane **14** and a number of pressure sensors **20** which are located to detect forces applied by one or more indentors to membrane **14**.

[0020] Membrane **14** may be fabricated from a broad selection of materials and may be fabricated by a variety of processes. Membrane **14** is preferably flexible and elastic. The flexibility and modulus of elasticity of membrane **14** are determined by the material(s) from which membrane **14** is made, the manufacturing processes used to make membrane **14**, the thickness of membrane **14**, and the shape of membrane **14**. These parameters are referred to as "physical parameters" of membrane **14**.

[0021] Membrane **14** may comprise a wear surface **16**. Wear surface **16** may comprise one or more layers of material. Membrane **14** may serve several purposes - it provides a durable wear surface, it protects pressure sensors **20** from the environment and it can distribute applied pressures over multiple sensors **20**. Membrane **14** may be constructed so that it concentrates applied forces over individual pressure sensors **20**, thereby increasing the sensitivity of system **10**.

[0022] Wear surface **16** may provide an appropriate aesthetic or tactile nature. Wear surface **16** may comprise one or multiple layers. The one or more layers may each comprise any of a wide variety of materials, including polyurethane, polyester, polycarbonate, rubber, fabric, leather, and almost any other flexible material. In some cases, graphics may be printed on layers of wear surface **16** or membrane **14**. The layers of wear

surface **16** may be thick or thin, or of varying thickness. In some embodiments membrane **14** may include or overlie a layer of a compressible material between wear surface **16** and substrate **12**.

[0023] There are a plurality of pressure sensors **20** on substrate **12**. Pressure sensors **20** may comprise individual pressure sensors, or, may comprise a distributed presure sensor such as the cellular-type pressure sensor described in WO 00/73982. A pressure sensing arrangement of this type comprises a pad made of a compressible medium such as, cellular foam, which is semi-transparent or translucent to light. Compression of the medium alters the intensity of light detected by light sensors in an array of optical sensors. A signal processing unit translates the resulting signal into a determination of the location of force applied to the pressure sensing surface. The optical components and signal processing unit are not shown herein, but are fully described in WO 00/73982, which is incorporated herein by reference.

[0024] The specific type of pressure sensor **20** is not an essential aspect of the invention. Pressure sensors **20** may comprise sensors which measure deflection, forces or pressure. Pressure sensors **20** may comprise force-sensitive resistor elements. A sensor which can be used to sense forces applied to membrane **14** is referred to herein as a "pressure sensor", whatever the fundamental nature or mode of operation of the sensor may be. Pressure sensors **20** may be arranged in a regular array, such as a rectangular array or a hexagonal or triangular array. In some

embodiments, pressure sensors **20** may be irregularly distributed on substrate **12**.

[0025] The physical properties of membrane **14** may be selected and made to vary across membrane **14** in ways which alter the manner in which forces applied by indentors pressing on the upper surface **17** of membrane **14** are transmitted to sensors **20**.

[0026] In the embodiment of Figure 1, membrane **14** is substantially flat and has protrusions **18** formed on its underside **15** (the side adjacent substrate **12**). Protrusions **18** are positioned to overlie individual pressure sensors **20**. Protrusions **18** contact pressure sensors **20**. Elsewhere there is a space **21** between substrate **12** and underside **15** of membrane **14**. Protrusions **18** may optionally be adhered to pressure sensors **20**.

[0027] Forces applied to the upper surface of membrane **14** are distributed to pressure sensors **20** by way of protrusions **18**. Protrusions **18** concentrate downward forces applied to surface **16** over a subset of pressure sensors **20**. This increases the sensitivity of system **10** and, by distributing the pressure over a number of pressure sensors **20**, it facilitates accurate determination of the locations of applied forces.

[0028] Protrusions **18** may have various configurations. Protrusions **18** may include bumps which may be circular or other shaped, or straight or curved ridges. Protrusions may also be provided on top surface **17** of

membrane **14**. The protrusions typically increase the stiffness of membrane **14**. Membrane **14** may also, or in the alternative, comprise areas of weakness. Areas of weakness may be provided by cuts or holes in the membrane, recessed regions, regions in which the membrane is made of a different material or composition, or regions in which one or more layers of the membrane are not present, are of different thickness, etc. The thickness of membrane **14** may vary over its area.

[0029] In some applications, it is desirable to provide a membrane system divided into two or more separate areas, each of which can independently measure the location(s) and force(s) applied to the area by one or more indentors. Figure 2 illustrates a membrane system **10**, comprising substrate **12** overlain by membrane **14**. Membrane **14** is divided into two areas **24a** and **24b** by a divider **22**. In the Figure 2 embodiment, divider **22** comprises a slot **23**. Because membrane **14** is interrupted by slot **23**, it does not distribute applied force from one area **24** to the other. Due to the discontinuity in membrane **14**, indentors applying force in area **24a** have no effect on the pressure signals generated by sensors **20** associated with area **24b**, and *vice versa*. A membrane system **10** according to the invention may be divided into a plurality of separate areas of desired sizes and shapes by providing suitable dividers **22**.

[0030] Dividers **22** may be formed by one or more of slots or other weakened regions within membrane **14** and regions of membrane **14** which contact substrate **12**. Regions which contact substrate **12** may be

trough-like in shape to isolate separate regions on either side of the trough. In the alternative, in these regions, membrane **14** may have bumps, ridges, or other protrusions which contact substrate **12**.

[0031] Figures 3 and 4 illustrate a further embodiment in which membrane **14** is divided into separate areas. In this embodiment, divider **22** comprises a region **30**. In region **30** membrane **14** is adhered to substrate **12**. Region **30** divides membrane **14** into two areas. Firmly affixing membrane **14** to substrate **12** between areas **32a** and **32b** prevents vertical forces from being transmitted from one area to an adjacent area. This isolates the areas. Divider **22** also affects the distribution of forces among pressure sensors **20** associated with areas **32**. Where divider **22** comprises recessed region **30**, recessed region **30** supports some applied load, and effectively stiffens membrane **14** near edges of areas **32a** and **32b**. In certain applications this can be used to advantage.

[0032] Dividers **22** may be designed in an application-specific manner. For example, consider an application wherein a touch surface is to be divided into two separate areas along its length (see Figure 3) by recessed regions **30**. In this example, touching within area **32a** will not affect sensors in the adjacent area **32b**. By constructing membrane **14** with recessed regions **30** (which are firmly fixed to substrate **12**) along the long edges of areas **32a** and **32b**, membrane **14** is made to be more rigid. This provides an additional effect: the distribution of forces along the length of each area **32** (i.e. within each area **32**) is diminished. As a

result, pressure sensors **20** within each area **32** are also de-coupled (to some extent), even though there is not a physical feature dividing pressure sensors **20** within either area **32**.

[0033] Consider another application where a touch surface is to be divided along its length by slot **23** as in Figure 2. Like areas **32a** and **32b**, areas **24a** and **24b**, separated by slot **23**, are isolated in that force applied to one area has no effect on the other area. However, each area **24a** and **24b** provides a continuous sensory surface. Several pressure sensors **20** respond to force applied on an indentor placed anywhere in either area.

[0034] The pressure distribution of membrane **14** can be tailored for specific applications. A combination of physical features (holes, slots, recessed regions, protrusions, bumps, ridges, varying thickness, etc.) may be used to achieve a variety of performance characteristics. One can think of these physical features as a set of tools to be used to create the desired performance characteristics.

[0035] In some cases, a regular, rectangular arrangement of pressure sensors **20** is preferred. In other applications, however, pressure sensors **20** may be arranged irregularly. The distribution of force by an indentor applied to pressure sensors **20** is determined by the physical parameters of membrane **14** (as described above). In combination with careful design of the physical parameters, the number of pressure sensors **20** may be minimized while still achieving a desired performance.

[0036] Figures 5 and 6 illustrate a membrane system **10** according to an alternative embodiment of the invention. Membrane system **10** comprises substrate **12** covered by membrane **14**. Membrane **14** is divided into areas **31** of various shapes and orientations by a combination of recessed regions **30** and slots **23.** Isolated areas **31** may comprise rectangles, truncated triangles and various irregular shapes. The arrangement illustrated in Figure 5 is only an example and is not intended to be limiting. Many arrangements of areas **31** may be defined within membrane **14**.

[0037] Figure 7 shows a membrane system **10** according to a further embodiment of the invention. In the embodiment of Figure 7, substrate **12** comprises a number of cells **40**. Each cell **40** comprises an optical cavity **42** filled with a pressure-sensitive medium **44**. Cells **40** are arranged to define isolated areas **46a** and **46b** of the overlying membrane **14**. Pressure detecting means are provided in each area **46**. The pressure detecting means may comprise a plurality of optical receiver/transmitter pairs **48** positioned in each cavity **42** underneath pressure-sensitive medium **44**. Areas **46a** and **46b** are isolated from one another by isolating means. In the embodiment illustrated in figure 7, the isolating means comprises the portion **50** of membrane **14** attached to substrate **12** between cavities **42**.

[0038] Any one of the membrane systems described above may be combined with a controller which derives information about the location

and force applied to membrane **14** by one or more indentors from the signals generated by pressure sensors **20**. The controller may provide outputs which identify the locations of one or more indentors in a suitable one-dimensional or two-dimensional coordinate system. The controller may also provide outputs which indicate the magnitude of the forces being applied at the locations of the indentor(s).

[0039] It is often desirable to know the location at which an indentor applies pressure to membrane system **10**. Consider the case of an indentor applying a force upon membrane **14**. In some prior art pressure sensors, the location of an indentor is determined by computing the "centre-of-mass" of the pressure signals. The process can be generalized to compute the locations of several indentors by a variety of different algorithms which determine a subset of pressure sensors corresponding to each indentor; a centre-of-mass or similar algorithm is then used on each subset to compute the location of the corresponding indentor. It is generally accepted that, for accurate centre-of-mass calculation, the sensors should be located in a regular rectangular array. That restriction is not necessary for this invention.

[0040] The pressure signal from a (properly calibrated) pressure sensor **20** depends on the force applied to membrane **14** and the distance from the centre of the indentor to the pressure sensor **20** as follows:

$$v_i = V(w, r_i) \quad (1)$$

where v_i is the pressure signal of the i^{th} sensor, w is the downward force applied by the indentor and r_i is the distance from the indentor to the i^{th} sensor. The inventors have determined that the function V can be represented as a product of two functions, one dependent only on w, and the other dependent on the distance between the indentor and the sensor as follows:

$$V(w,r_i) = V_w(w)V_{r,i}(r_i) \qquad (2)$$

where V_w is a function which depends only on the force applied and $V_{r,i}$ is a function which depends only on the distance. Pressure sensors **20** are preferably chosen such that the function $V_w(w)$ is the same for all sensors. The function $V_{r,i}(r_i)$ may be different for each sensor, depending on the physical features of membrane **14**. To calibrate membrane system **10**, one applies a number of known forces to a number of known locations on membrane **14** and measures v_i from each pressure sensor **20** for each known force. Well known numerical methods are then used to determine $V_w(w)$ and $V_{r,i}(r_i)$.

[0041] The following examples relate to systems comprising a pressure-sensitive surface comprising an array of individual sensor elements, and a controller for receiving pressure information from the sensor elements. The controller is programmed to determine the location and optionally the amount of pressure applied by an indentor to the pressure-sensitive surface with a high degree of precision. The examples relate to various specific sensor arrays and controller functions.

Example 1: Computing the location of applied pressure

[0042] Consider a pressure-sensitive surface comprising a single straight row of sensors, onto which a membrane is applied. The coordinate x is used to specify the distance along an axis through the centers of the sensors from an arbitrary origin. In this example, the distance between the indentor and a sensor is simply $r_i = x - x_i$, where x is the location of the indentor and x_i is the location of sensor i.

[0043] The problem is to determine the location x and the applied force w, for known set of v_i, and x_i, $i = 1,\ldots, N$. One could compute the location x by the following formula:

$$x \approx \hat{x} = \frac{\sum_{i=1}^{N} x_i v_i}{\sum_{i=1}^{N} v_i} \qquad (3)$$

where $\hat{x}$ is the estimated value of x. Equation (3) explicitly depends on the locations of the sensors, x_i, and implicitly depends on the physical parameters of the membrane. As a result, in general $x \neq \hat{x}$. Another way of stating this is that due to the shape of the function $V_{r\,i}$, $\hat{x}$ may not be an accurate estimate of x.

[0044] This invention provides a method for accurately determining x. The following is the mathematical basis for this aspect of the

invention. Substituting Equations (1) and (2) into Equation (3) yields:

$$\hat{x} = \frac{\sum_{i=1}^{N} x_i V_w(w) V_{r,i}(x - x_i)}{\sum_{i=1}^{N} V_w(w) V_{r,i}(x - x_i)} = \frac{\sum_{i=1}^{N} x_i V_{r,i}(x - x_i)}{\sum_{i=1}^{N} V_{r,i}(x - x_i)} \qquad \textbf{(4)}$$

where $V_w(w)$ has been removed from the summation since it does not depend on i. As a result of Equation (2), the estimated location, $\hat{x}$, does not depend on the applied force. For convenience, we define the function $h(x)$ as:

$$h(x) \equiv \frac{\sum_{i=1}^{N} x_i V_{r,i}(x - x_i)}{\sum_{i=1}^{N} V_{r,i}(x - x_i)} \qquad \textbf{(5)}$$

[0045] One can define the inverse of $h(x)$ to be the function H as follows:

$$H(h(x)) = x \qquad \textbf{(6)}$$

[0046] H can be determined experimentally by acquiring pressure signals from sensors **20** as a known force is applied to membrane **14** at various positions along the x-direction. The acquired data may be used to compute $\hat{x}$ as a function of x. Inverting the functional dependence yields x as a function of $\hat{x}$, which is the function H.

[0047] One could also determine H numerically by applying Equations (5) and (6) using analytical expressions for the function $V_{r,i}$. Since H is independent of w, it is dependent only on the physical parameters and the geometry of membrane **14**, so it needs to be determined only once. i.e. it can be determined in advance of use and called upon as required in an application. Having determined the function H, one can determine the location of an indentor by computing $\hat{x}$ by Equation (3) and then computing x as follows:

$$x = H(\hat{x}) \tag{7}$$

where x is the solution to the problem which was posed.

[0048] To summarize, one can compute x by application of the following algorithm:

- determine the function H beforehand, by experimentation or analysis and store a representation of H;
- during operation compute $\hat{x}$ from known v_i and x_i, by Equation (3); and,
- during operation determine x by computing $x = H(\hat{x})$.

[0049] H may be stored as a function, a lookup table containing values at representative points of H, as a set of parameters which defines a function which approximates H - e.g. a set of polynomial coefficients, or the like.

[0050] To determine the magnitude of the applied force, one takes the sum of the pressure signals:

$$\sum_{i=1}^{N} v_i = \sum_{i=1}^{N} V_w(w) V_{r,i}(x - x_i) = V_w(w) \sum_{i=1}^{N} V_{r,i}(x - x_i) \qquad (8)$$

[0051] This expression could be used as an estimate of the applied force, w. However, $\sum v_i$ is dependent on x. Thus the same applied force can result in different computed values of $\sum v_i$, depending on the location of the indentor. To facilitate computation of the applied force, w, we define the function:

$$W(w) \equiv \frac{V_w(w)}{V_w(w_0)} \qquad (9)$$

where w_0 is a specified (constant) applied force. Rearranging this and substituting it into Equation (8), yields:

$$\sum_{i=1}^{N} v_i = W(w) V_w(w_0) \sum_{i=1}^{N} V_{r,i}(x - x_i) = W(w) \left[\sum_{i=1}^{N} v_i \right]_{w=w_0} \qquad (10)$$

[0052] The function $f(x)$ is defined as follows:

$$f(x) \equiv \left[\sum_{i=1}^{N} v_i \right]_{w=w_0} \qquad (11)$$

which depends only on x, since the summation is evaluated at a known force w_0. Inherent in $f(x)$ are the geometric and physical parameters of the

membrane. In practice, $f(x)$ can easily be determined by applying force w_0 to the membrane with an indentor at a number of positions x, and computing the sum of the sensor responses for each position of the indentor. The relationship between the position x and the sum of responses (for force w_0) is the function $f(x)$.

[0053] Alternatively, if a mathematical model of the sensor response is known, then the function $f(x)$ may be determined analytically or numerically. The function $f(x)$ need only be determined once and may be called upon as required during operation. Having determined the function $f(x)$, and having computed x previously, computation of the function $W(w)$ follows by application of Equation (8) as follows:

$$W(w) = \frac{\sum_{i=1}^{N} v_i}{f(x)} \tag{12}$$

[0054] Importantly, $W(w)$ does not depend on the coordinates of the indentor because of the assumption of Equation (2) and the definition of $W(w)$. Even though the indentor position is used in the computation of $f(x)$, and therefore in the computation of $W(w)$, the division of $\sum v_i$ by $f(x)$ exactly counteracts any positional dependency in $\sum v_i$.

[0055] In practice, knowing the value of W is generally sufficient since W is a single-valued monotonic function of w. However, in applications where it is important to know w exactly, then the function

$V_w(w)$ of Equation (9) can be inserted and the inverted function used to compute w as follows:

$$w = V_w^{-1}(W(w)V_w(w_0)) \tag{13}$$

where $V_w^{-1}(W)$ is the inverse of $V_w(w)$.

<u>Example 2: Computation for an x-y-pad</u>

[0056] Consider a two-dimensional pressure-sensitive surface whereupon we wish to compute the location of the indentor in two dimensions using a Cartesian coordinate system. The method described here can also be applied for other frames of reference. An indentor applies a downward force of magnitude w at coordinates (x,y). As before, we assume that the pressure response of the sensors satisfies Equation (2). In this case, however, the distance r is given by:

$$r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \tag{14}$$

where (x_i, y_i) are the coordinates of sensor i.

[0057] The location of the indentor could be computed as follows:

$$\hat{x} = \frac{\sum_i x_i v_i}{\sum_i v_i} \tag{15}$$

$$\hat{y} = \frac{\sum_i y_i v_i}{\sum_i v_i} \tag{16}$$

[0058] However, in general, $\hat{x}$ and $\hat{y}$ will not accurately determine x and y. In general, $\hat{x}$ will differ from x by an amount that depends on x and y.

[0059] This invention provides a method for accurately determining x and y. Substituting Equation (2) into Equation (15) and (16) and simplifying yields:

$$\hat{x} = \frac{\sum_i x_i V_{r,i}(r_i)}{\sum_i V_{r,i}(r_i)} \tag{17}$$

$$\hat{y} = \frac{\sum_i y_i V_{r,i}(r_i)}{\sum_i V_{r,i}(r_i)} \tag{18}$$

[0060] $V_w(w)$ is independent of i and can therefore be removed from the summation. Equations (17) and (18) show that, under the assumption of Equation (2), both $\hat{x}$ and $\hat{y}$ are independent of the applied force. The functions $h(x,y)$ and $g(x,y)$ are defined as follows:

$$\hat{x} = h(x,y) \equiv \frac{\sum_i x_i V_{r,i}(r_i)}{\sum_i V_{r,i}(r_i)} \tag{19}$$

$$\hat{y} = g(x,y) \equiv \frac{\sum_i y_i V_{r,i}(r_i)}{\sum_i V_{r,i}(r_i)} \tag{20}$$

The system of Equations (19) and (20) is then solved for (x,y) in terms of $(\hat{x},\hat{y})$. The functions H and G are defined as follows:

$$\begin{aligned} x &= H(\hat{x},\hat{y}) \\ y &= G(\hat{x},\hat{y}) \end{aligned} \qquad \textbf{(21)}$$

[0061] As with Example 1, if an exact mathematical model of the pressure response is known, the functions H and G may be determined analytically or numerically. It is straightforward in practice to determine H and G experimentally. This can be done by applying a downward force to the membrane at a number of known positions (x,y), and computing $(\hat{x},\hat{y})$ for each of the known positions from the responses of the pressure sensors when the downward force is being applied at those known positions. The relationship between x and $(\hat{x},\hat{y})$ is H, and the relationship between y and $(\hat{x},\hat{y})$ is G. The relationships H and G need only be determined once for a given design of pressure sensing surface - they are dependent on the geometry and physical parameters of the membrane. Having determined the functions H and G, the coordinates of the indentor location can be determined during operation by computing $(\hat{x},\hat{y})$ in accordance with Equation (15) and (16) and then applying Equation (21).

[0062] It remains to compute the magnitude of the applied force. This follows a similar derivation as in Example 1. First define the

parameter $W(w)$ as in Equation (9). $W(w)$ does not depend on the location (x,y) of the indentor. Rearranging Equation (9), yields $V_w(w) = W(w)V_w(w_0)$. Substituting this and Equation (2) into Equation (15) yields after simplification:

$$\sum_i v_i = W(w)\left[\sum_i v_i\right]_{w=w_0} \quad (22)$$

which is identical to Equation (10). One then defines a new function:

$$f(x,y) \equiv \left[\sum_i v_i\right]_{w=w_0} \quad (23)$$

[0063] $f(x,y)$ is dependent only on the coordinates (x,y) of the indentor since the summation is evaluated at a known force w_0. Inherent in $f(x,y)$ are the geometric and physical parameters of the membrane. In practice, $f(x,y)$ can easily be determined by applying force w_0 to the membrane with an indentor at a number of known positions (x,y) and computing the sum of the sensor responses. The relationship between the position (x,y) and the sum of responses (for force w_0) is the function $f(x,y)$. Alternatively, if a mathematical model of the sensor response, Equation (1) is known, then $f(x,y)$ may be determined analytically or numerically. $f(x,y)$ need only be determined once and may be called upon as required during operation. Having determined $f(x,y)$, and having computed (x,y) previously, computation of the applied force follows by application of Equation (22) as follows:

$$W(w) = \frac{\sum_i v_i}{f(x,y)} \qquad \textbf{(24)}$$

[0064] In practice, knowing the value of *W(w)* is generally sufficient since it is a single-valued monotonic function of *w*. Importantly, *W(w)* does not depend on the location of the indentor (even though knowledge of those coordinates was used to compute *f(x,y)*). In essence, division by *f(x,y)* exactly counteracts the positional dependency of $\sum_i v_i$.

[0065] In applications where it is important to know *w* exactly, then the function $W(w)$ can be inverted and the inverted function used to compute *w*. In order to do this, an analytic or numerical model for $V_w(w)$ is required, and then the definition of $W(w)$, Equation (9), can be applied as follows:

$$w = V_w^{-1}(W(w)V_w(w_0)) \qquad \textbf{(25)}$$

where $V_w^{-1}(W)$ is the inverse of $V_w(w)$.

<u>Example 3: Special case of an xy-pad with row-column sensor arrangement</u>

[0066] Consider the case where the pressure sensors have been arranged in a series of straight rows and straight columns. For convenience we chose the coordinate frame of reference, F_{xy}, to be oriented along the rows and columns. It is not necessary that the rows and columns be equally spaced, but it is stipulated that the pressure

sensors are located at the every intersection of the imaginary straight lines which represent the rows and columns.

[0067] For this example, we introduce another assumption: the function $V_r(x,y)$ can be separated into the product of two functions as follows:

$$V_r(r)=V_x(\Delta x)V_y(\Delta y) \tag{26}$$

where r is related to Δx and Δy by $r=\sqrt{\Delta x^2+\Delta y^2}$. Expanding Equation (2) with this assumption yields:

$$V(w,r)=V_w(w)V_x(\Delta x)V_y(\Delta y) \tag{27}$$

[0068] In terms of an individual sensor response, this is written as

$$v_i=V(w,r_i)=V_w(w)V_{x,i}(\Delta x_i)V_{y,i}(\Delta y_i) \tag{28}$$

where v_i, is the pressure signal of sensor i located at coordinates (x_i,y_i), w the downward force applied by an indentor at coordinates (x,y), and $(\Delta x_i, \Delta y_i)$ is the difference in coordinates between the sensor and the indentor: $\Delta x_i=x-x_i$, $\Delta y_i=y-y_i$. It can be verified by experimentation that touch sensitive surfaces fabricated in accordance with the foregoing do in fact satisfy Equation (28) to very close approximations.

[0069] Substituting Equation (28) into Equation (15) and simplifying yields:

$$\hat{x} = \frac{\sum_i x_i V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i)}{\sum_i V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i)} \qquad \textbf{(29)}$$

[0070] Since the sensors are arranged regularly, it follows that for each row of sensors, $y_i = y_j$, for sensors i, j in the same row. So $V_y(\Delta y_i) = V_y(\Delta y_j)$ for sensors in the same row. Then:

$$\begin{aligned}\hat{x} &= \frac{\sum_{Row1} x_i V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i) + \sum_{Row2} x_i V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i) + \ldots + \sum_{RowM} x_i V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i)}{\sum_{Row1} V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i) + \sum_{Row2} V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i) + \ldots + \sum_{RowM} V_{x,i}(\Delta x_i) V_{y,i}(\Delta y_i)} \\ &= \frac{V_y\big|_{Row1} \sum_{Row1} x_i V_{x,i}(\Delta x_i) + \ldots + V_y\big|_{RowM} \sum_{RowM} x_i V_{x,i}(\Delta x_i)}{V_y\big|_{Row1} \sum_{Row1} V_{x,i}(\Delta x_i) + \ldots + V_y\big|_{RowM} \sum_{RowM} V_{x,i}(\Delta x_i)}\end{aligned} \qquad \textbf{(30)}$$

where $V_y\big|_{RowK}$ is the value of $V_y(\Delta y_i)$ for any sensor located in row K.

Since the sensors are arranged regularly, it follows that

$\sum_{RowK} x_i V_{x,i}(\Delta x_i) = \sum_{RowL} x_i V_{x,i}(\Delta x_i)$ and $\sum_{RowK} V_{x,i}(\Delta x_i) = \sum_{RowL} V_{x,i}(\Delta x_i)$

for all rows K, L. Therefore:

$$\hat{x} = \frac{\left\{ V_y \big|_{Row1} + V_y \big|_{Row2} + \ldots + V_y \big|_{RowM} \right\} \left\{ \sum_{Row1} x_i V_{x,i}(\Delta x_i) \right\}}{\left\{ V_y \big|_{Row1} + V_y \big|_{Row2} + \ldots + V_y \big|_{RowM} \right\} \left\{ \sum_{Row1} V_{x,i}(\Delta x_i) \right\}} = \frac{\sum_{Row1} x_i V_{x,i}(\Delta x_i)}{\sum_{Row1} V_{x,i}(\Delta x_i)} \quad \textbf{(31)}$$

In a similar manner, one derives:

$$\hat{y} = \frac{\sum_{Column1} y_i V_{y,i}(\Delta y_i)}{\sum_{Column1} V_{y,i}(\Delta y_i)} \quad \textbf{(32)}$$

[0071] Equations (31) and (32) show that under assumption (28), $\hat{x}$ is independent of the y-coordinate of the indentor and $\hat{y}$ is independent of the x-coordinate of the indentor. Both $\hat{x}$ and $\hat{y}$ are independent of the applied force. One thus writes:

$$\begin{aligned} \hat{x} &= h(x) \\ \hat{y} &= g(y) \end{aligned} \quad \textbf{(33)}$$

where h(x) and g(x) are defined to be the right-hand sides of Equations (31) and (32) respectively. Let us assume that we can invert the functions h(x) and g(x). That is, define the functions H and G as follows:

$$H(h(x)) = x$$
$$G(g(y)) = y$$

[0072] As with the one-dimensional case of Example 1, it is straightforward in practice to determine H and G experimentally. Then, knowing H and G, one determines (x,y) by:

$$\begin{aligned} x &= H(\hat{x}) \\ y &= G(\hat{y}) \end{aligned} \tag{34}$$

[0073] The system of equations (34) is much simpler that the corresponding system (21) for a general 2-dimensional surface. This example has shown that for pressure-sensitive surfaces constructed with straight rows and columns of sensors (even if they are not equally spaced), the computation of the location of the indentor is simplified by use of Equation (34) rather than Equation (21). Determination of the applied force follows in exactly the same manner as in the general case of Example 2.

[0074] The foregoing methods may be performed in a controller comprising a programmed data processor. The data processor could comprise, for example, one or more microprocessors. The one or more processors in the controller may implement the methods of the invention by executing software instructions in a program memory accessible to the one or more processors. Calibration information including a

representation of H and, where appropriate, G may be stored in a data store in or otherwise accessible to the controller.

[0075] The invention has a wide range of possible applications including key pads for electronic equipment, controllers for electronic musical equipment, and the like.

[0076] The invention may also be provided in the form of a program product. The program product may comprise any medium which carries a set of computer-readable signals comprising instructions which, when executed by a computer processor, cause the data processor to execute a method of the invention. Program products according to the invention may be in any of a wide variety of forms. The program product may comprise, for example, physical media such as magnetic data storage media including floppy diskettes, hard disk drives, optical data storage media including CD ROMs, DVDs, electronic data storage media including ROMs, flash RAM, or the like or transmission-type media such as digital or analog communication links.

[0077] Where a component (e.g. a software module, processor, assembly, device, circuit, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which

performs the function in the illustrated exemplary embodiments of the invention.

[0078] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example, the novel methods for locating a position at which an indentor contacts a surface of a pressure-sensitive device described herein may be applied with types of pressure-sensitive structure other than those described in the preceding description. These methods may also be applied to locate points at which indentor(s) contact certain prior art pressure-sensitive devices. The methods for determining a magnitude of a force applied to an indentor may also be used with pressure-sensitive devices other than those described in the preceding description including certain prior art pressure-sensitive devices. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.